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PREDICTION OF WATER ABSORPTION OF NONGLAZED TILES MADE BY SEMIDRY MOLDING USING A REGRESSION MODEL

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The possibility of predicting water absorption in semi-dry molding of ceramic tiles using data on linear dimensions of molded tiles and their firing regime is considered. An empirical formula is given, which makes it possible to estimate the quantitative effect of tile sizes, molding pressure, and firing parameters on the variations in water absorption. The possibility is demonstrated for predicting water absorption in tiles 40 – 50 min before they leave the firing furnace.

One of the most significant quality parameters in ceramic tile production by semi-dry molding on conveyor lines is water absorption of fired tiles. It is known [1] that this parameter depends on the chemical and granulometric composition of ceramic mixtures, initial moisture content of powders, molding pressure, firing temperature, and firing duration. These parameters in tile production are periodically monitored. However, there is yet no mathematical relationship which would make it possible to evaluate the effect of each of the main factors on sintering of ceramic tiles.

The object of the present study was to obtain a mathematical regression model which would make it possible to predict water absorption using the data on linear dimensions of molded tiles and their main production parameters. The aim was to predict the water absorption 40 – 50 min before the tiles leave the firing kiln, which would make it possible, if necessary, to correct the firing regime and the basic initial technological parameters. As a consequence, the quality of tiles can be improved and in some cases natural gas can be saved by decreasing the firing temperature, if the water absorption of tiles is significantly below the prescribed standard value.

For this purpose, a series of experiments was carried out at the Keramin company (Minsk) on SMK-158 conveyor lines of nominal annual capacity of 400 thousand m^2 floor tiles, which operate in coordination with molding machines equipped with a one-cavity mold.

The nonglazed floor tiles were made of molding powders of 5 – 8% moisture based on tinted mixtures.

The mixture compositions included (%, hereinafter weight content is indicated): 70 – 72 clay component, 24 – 28 fluxing additive, 4 – 6 chamotte (crushed broken or rejected tiles). The clay component of yellow mixtures was a strictly dosed quantity of clay brought from the Veselovskoe, Druzhkovskoe, and (or) Nikolaevskoe deposit, and the red-burning mixture contained clay from the Nikiforovskoe and Druzhkovskoe deposits. The fluxing additive was a combined flux which contained glass cullet and nepheline-sienite or, less frequently, perlite.

The chemical composition of the mixtures during the experiment varied insignificantly and was within the following limits: for the yellow mixtures (%): 58.9 – 60.8 SiO_2, 23.1 – 27.0 Al_2O_3, 0.7 – 2.2 TiO_2, 2.7 – 3.0 Fe_2O_3, 1.3 – 2.5 CaO, 1.0 – 1.9 MgO, 2.3 – 2.9 K_2O, 4.6 – 5.1 Na_2O; for the red-brown mixtures (%): 63.0 – 65.2 SiO_2, 20.0 – 21.4 Al_2O_3, 1.0 – 1.2 TiO_2, 4.9 – 5.2 Fe_2O_3, 1.9 – 2.1 CaO, 1.8 – 2.0 MgO, 0.9 – 1.1 K_2O, 4.0 – 4.3 Na_2O. Thus, the amount of fluxing additives of the type (R_2O + RO +Fe_2O_3) in the composition of the yellow mixtures was 12.0 – 15.4%, and in the red-brown mixtures, 13.4 – 14.7%. The ratio RO:R_2O varied within the limits of 0.33 – 0.55 and 0.74 – 0.76, respectively.

The granulometric composition of molding powders exhibited the following ratio of fractions: 2.0 – 1.0 mm — 8.0%, 1.0 – 05 mm — 13%, 0.5 – 025 mm — 57.0%, below 0.25 mm — 22.0%. The deviation from the specified fraction content was ± 1%.

X-ray phase analysis indicated that the main crystal phases in the yellow-colored mixtures for all experimental series was quartz, plagioclase, and small quantities of a compound of the type CaO · 3FeO · Fe_2O_3. The crystal phase in the red-brown mixtures was represented by quartz, anorthite, hematite, and a small amount of augite. Studies of the arbitrary concentration of the main crystal phases revealed that the quartz content varied from 63 to 66%, the plagioclase content was 10 – 13%, and the content of ferrous compounds

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was 3 – 5%, which is the evidence of the similarity in the phase compositions of the synthesized materials.

Data collection for constructing a mathematical regression model consisted in sampling semifinished tiles from the molding machines at an interval of 4 – 5 min, after which the tiles were weighed on an electronic scale, and their average sizes were determined by multiple measuring of size L and height h. The molding pressure was recorded by averaged readings of the molding machine manometer. The moisture content of tiles was determined after their drying in a drying cabinet at temperature 105 ± 5°C and subsequent weighing. After sampling tiles from the molding machine, the time that the tiles placed on the conveyor spent in the firing kiln sections at maximum temperature was calculated, as well as the duration from the moment of molding to the moment the tiles left the maximum temperature zone for the sorting zone. The readings of the thermocouples inside the firing kiln were recorded by KSP-4 recording potentiometers.

The water absorption of fired samples was determined by boiling in water for 1 h (V_b) and by an accelerated method which involved the saturation of tiles in vacuum on a ECW device (express control of water absorption) W_{ecw}, according to the standard methods (GOST 27180–86, GOST 6787–90).

Table 1 gives the experimental data processing results: the average value of molding pressure according to the manometer P, the initial moisture W, the side length of a square tile L, the firing duration τ_f, and the average temperature t_{av} for three sections of the roller kiln in which the highest firing temperatures were observed. Table 1 also shows the ratio of the current tile volume V to the average volume V_{av} in the sampling. The average tile volumes for two samplings in the experimental series performed are equal to 3.2498×10^{-4} and 2.7266×10^{-4} m^3, respectively. Splitting the entire data body in two samplings is due to the fact that the company manufactures tiles 12 and 10 mm high.

The volume of the tile was calculated from the formula

$$V = L^2 h \tag{1}$$

The tile density ρ (Table 1) is determined from the expression

$$\rho = m_m / V \tag{2}$$

where m_m is the mass of the moist tile, kg.

Table 1 also contains the number of the first of the two kiln sections N_s with the highest firing temperature.

Using the software package by the stepwise regression method [2, 3], we obtained a regression model of water absorption (boiling) V_{cr} as a function of the number of main technological parameters in tile production

$$\begin{aligned} V_{cr} = &-309.316 + 7259.94L^2 + 270.272(V/V_{av}) \\ &- 136.127(V/V_{av})^2 + 7.38527P - 0.644427P^2 \\ &- 1.05005 \times 10^{-2}\rho - 2.27758 \times 10^{-3}\tau_f \\ &+ 0.036166N_c^2 - 1.35004 \times 10^{-5}(t_{av})^2. \end{aligned} \tag{3}$$

Table 1 also shows water absorption V_{cr} calculated from Eq. (3). The mean quadratic deviation V_{cr} determined from Eq. (3) comprises 0.22%, and the correlation coefficient is equal to 0.963.

Figures 1 and 2 reflect the variation in water absorption as a function of molding pressure, tile parameters, and firing conditions. The minimum contribution of water absorption to

TABLE 1

Experiment number	Line number	P, MPa	W, %	L, m	V/V_{av}	ρ, kg/m^3	τ_f, sec	N_s	t_{av}, °C	V_b, %	V_{cr}, %	V_{ecw}, %
1	2	6.82	4.33	0.16420	1.0230	1845	3732	11	1016	3.28	3.41	3.34
2	7	5.89	5.30	0.16394	0.9932	1891	2940	9.5	1018	3.99	3.82	3.82
3	3	6.06	4.72	0.16349	0.9985	1948	3720	11	1006	1.78	1.76	2.10
4	9	6.18	4.82	0.16467	1.0296	1801	3012	9.5	1035	5.55	5.57	5.34
5	1	6.80	4.36	0.16410	1.0466	1802	3546	9.5	1034	2.45	2.20	2.43
6	4	4.61	7.59	0.16399	0.9583	1881	3870	11	978	3.16	3.16	3.55
7	3	5.63	9.13	0.16365	0.9683	1991	3720	11	995	2.06	1.97	2.45
8	7	4.51	5.86	0.16412	1.0046	1832	3060	9.5	1030	3.30	3.31	3.12
9	2	6.82	7.24	0.16375	0.9756	1971	3732	12	1031	1.67	1.52	1.71
10	3	6.87	5.92	0.16380	0.9978	1930	3720	11	1001	1.90	2.06	2.78
11	7	6.77	6.06	0.16439	1.0219	1898	3240	9.5	976	4.60	4.47	4.48
12	1	5.27	5.98	0.16377	1.0033	1835	3528	10	978	3.95	3.96	3.91
13	9	5.40	6.67	0.16408	0.9440	1915	2940	10.5	1017	4.22	4.28	4.63
14	1	6.77	5.67	0.16390	0.9714	1892	3528	10	987	2.70	2.83	2.96
15	2	6.47	5.22	0.16388	1.0490	1857	3780	11	1001	2.93	2.92	3.29
16	7	6.28	5.75	0.16394	1.0370	1897	3240	9.5	1035	1.86	2.16	2.15

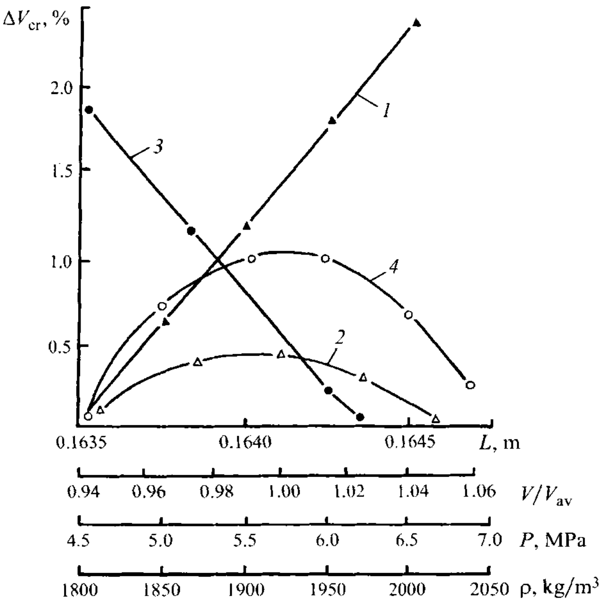

Fig. 1. Variation of water absorption as a function of tile width L (*1*), tile relative volume V/V_{av} (*2*), molded tile density ρ (*3*), and molding pressure P (*4*).

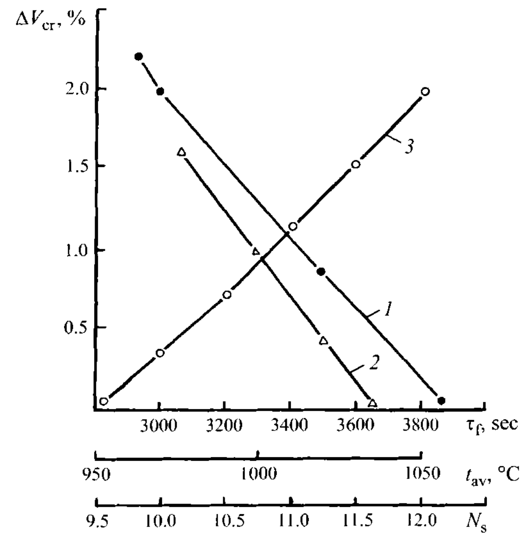

Fig. 2. Variation of water absorption of tiles as a function of firing duration τ_f (*1*), average firing temperature t_{av} (2), and kiln section number N_s (*3*).

the minimum or maximum variation range of each factor characterizing the tile is calculated from Eq. (3) and is taken as $\Delta V_{cr} = 0$.

An analysis of data in Fig. 1 shows that although curve *1* is a quadratic function of L, however, due to its narrow range, it is almost transformed into a straight line. Compared to other factors, the value L has the highest effect on water absorption. Thus, the variation of L from 0.16349 to 0.16467 m produces a variation in water absorption $\Delta V_{cr} = 2.81\%$. This is due to the fact that L depends on molding pressure and tile moisture: smaller tile sizes correspond to lower water absorption values.

Analysis of curves *2* and *4* established that water absorption also depends on the relative tile volume and molding pressure; however, it is hard to determine their full contribution based on the regression model, although the shape of the curves indicates that such a relationship exists. Therefore, to determine the contribution of each factor, it is necessary to consider the set of variation curves ΔV_{cr} depending on a number of other factors. It should be noted that as density increases, water absorption decreases.

Figure 2 shows that water absorption decreases as the average firing temperature in the three hottest kiln sections and firing duration increase, and becomes higher when the high-temperature zone in the kiln is shifted to the last section of the firing zone.

Note that the variations in the chemical and granulometric compositions are insignificant and are indirectly taken into account in Eq. (3) by means of such factors as relative volume, tile width, density, and molding pressure.

The performed studies show that the obtained regression model makes it possible to predict water absorption of molded tiles with rather high reliability prior to their exit from the firing kiln.

Thus, the proposed formula (3) makes it possible to estimate the quantitative effect of tile sizes, molding pressure, and firing parameters on water absorption variations. Further processing of the experimental data given in Table 1 will make it possible to obtain regression model systems and develop software packages for computer-aided prediction of water absorption of tiles 40 – 50 min before they leave the firing kiln.

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